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DAHLGREN DIVISION
NAVAL SURFACE WARFARE CENTER
Dahlgren, Virginia 22448-5100

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INFRARED REFRACTION AND MIRAGES

BY BILL TRAHAN
SHIP DEFENSE SYSTEMS DEPARTMENT

JANUARY 1995

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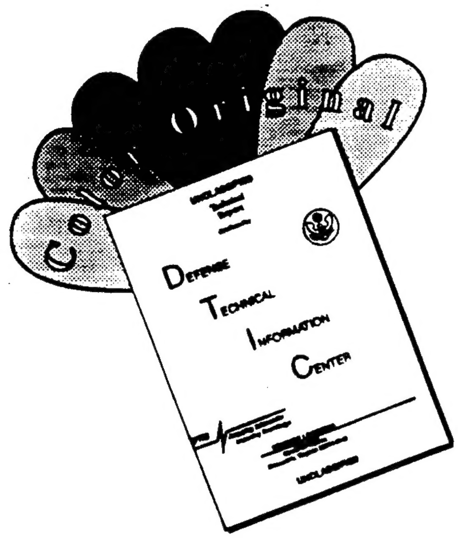

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FOREWORD

Mirages and other atmospheric refraction effects were observed and measured in the mid-wave infrared band (3 to 5 μm) during a recent field test. High-resolution recorded imagery is presented, including inferior and superior mirages. The affect of a superior mirage on target reporting by an infrared search and track simulation system is shown. This work is part of a continuing program to correlate IR refraction effects with simultaneous radio frequency propagation effects.

The following members of the horizon infrared surveillance sensor (HISS) and infrared propagation (IRP) test are acknowledged for their help in supplying data for this report between February and April 1994. The members of the HISS Test Team were Pat Dezeeuw (team leader), Everett Bryant, Robert Headley, Ken Hepfer, Connie Huffman, Keith Merranko, and Sheldon Zimmerman. The members of the IRP Test Team were Barry Henderson, Homar Rivera and Bill Trahan.

This report has been reviewed by Roger Carr, Head, Electro-Optical Systems Branch and Stuart Koch, Acting Head, Search and Track Division.

Approved by:

T. C. PENDERGRAFT, Head
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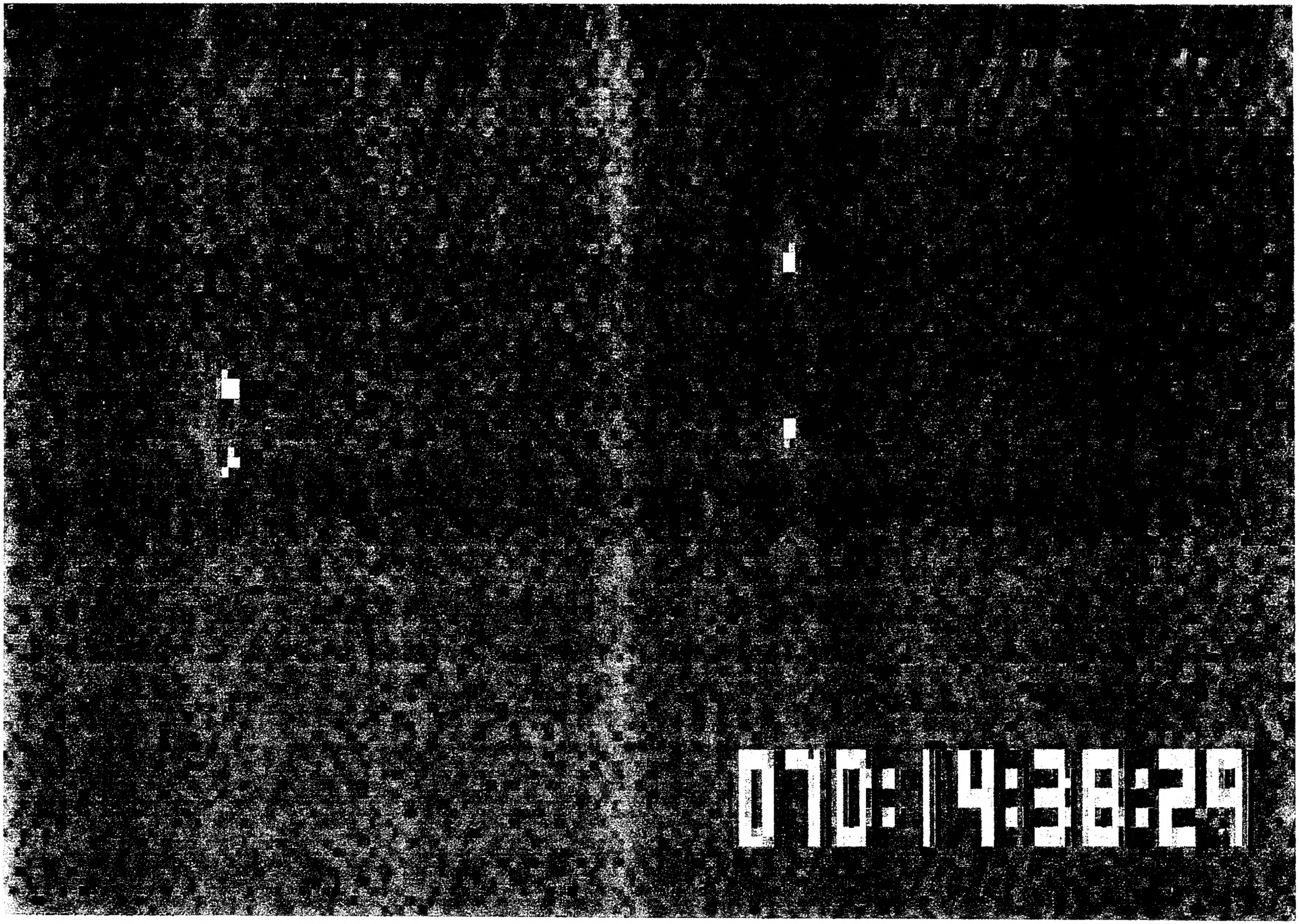
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Hello, my name is Bill Trahan. Today, I am going to discuss infrared refraction in the atmosphere and the formation of mirages. I will provide some measurements of infrared refraction, recorded during a recent field test, as well as images of mirages in the infrared.

Infrared Refraction and Mirages

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Wallops Island, Feb - Apr, '94

Bill Trahan
Electro-Optical Systems Branch, F44
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Refraction is the bending of light rays caused by changes in the propagation medium. In the atmosphere, the index of refraction at visible and infrared wavelengths varies with its density. Temperature, humidity, and pressure are the primary factors determining the density of the air. Near the Earth's surface, it is the vertical profile of air temperature, known as the lapse rate, that is the most important factor in determining infrared (and visible) refraction. Mirages are formed when atmospheric refraction begins to focus the light much as a lens would.

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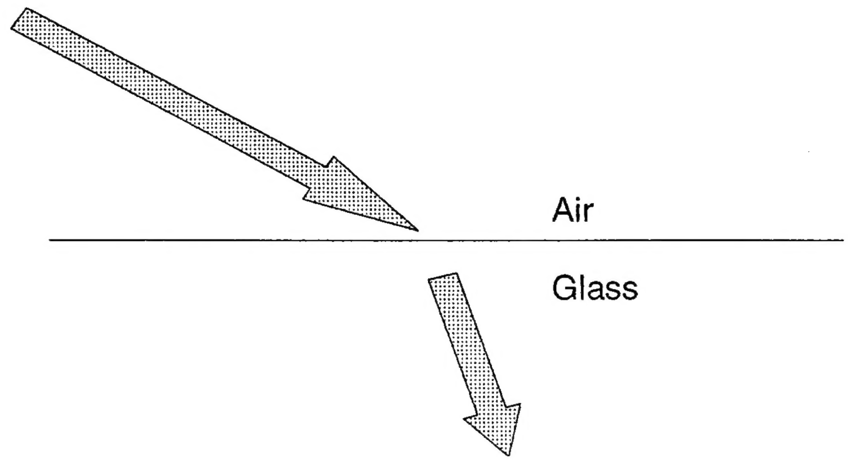

- Refraction is the bending of light rays as they pass obliquely through mediums with differing indexes of refraction.
- Changes in atmospheric density cause variations to the index of refraction. Although the variations are small, the long path lengths make the effect measurable.

Through the next few viewgraphs, the effect of different atmospheric conditions upon refraction will be contrasted.

First, as a baseline, neutral conditions are presented. These conditions occur when the air temperature does not change as a function of height. The concern here is with only the lowest 40 or so meters of the atmosphere.

Since the air temperature profile is difficult to measure directly, the air-sea temperature difference (ASTD) is the gauge most often used to indicate the atmospheric condition. The air temperature is measured at a height of 2 to 6 m. This height is not critical as most of the change occurs in the first meter above the water. Since the atmosphere is in thermal contact with the sea surface, the water temperature is assumed to equal the lowest atmospheric temperature.

- Jargon:
  - Air-Sea Temperature Difference (ASTD) — Zero
  - Atmospheric Condition — Neutral
  - Refractive Condition — Nominal

- Effects:
  - Convection — Some
  - Dip Angle — Normal
  - Horizon Range — Normal
  - Scintillation — Normal
  - Model Predictions — Fair

How the different atmospheric conditions affect the appearance of an image, using ray traces, is also shown.

The index of refraction as a function of height is modeled from a given set of meteorological data. With that, rays at various elevation angles are traced from the observer back to the source of the radiation. Along the rays that stop at the sea surface, the observer would see the water. Along those that proceed out of the top of the graph, the observer sees sky. The lowest ray that just skims the sea surface indicates the elevation angle of the horizon. The region of space to the right of the bundle of rays is beyond and below the horizon from the observer's perspective. The only way in which the observer can increase the maximum range to a target is to move to a higher altitude.

In the picture, a boat has been fixed at the same range as the horizon, approximately 8.5 nmi, in this case.

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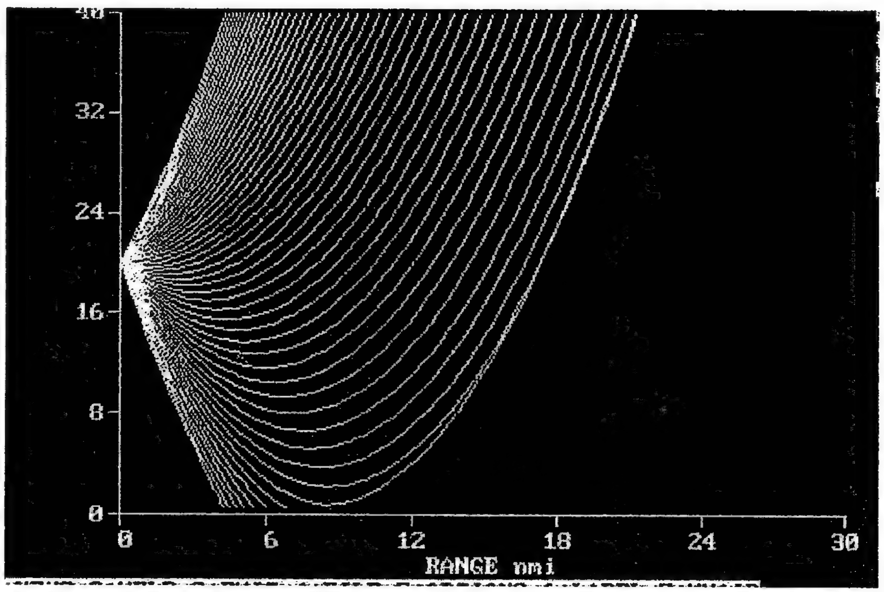
- Ray Trace:



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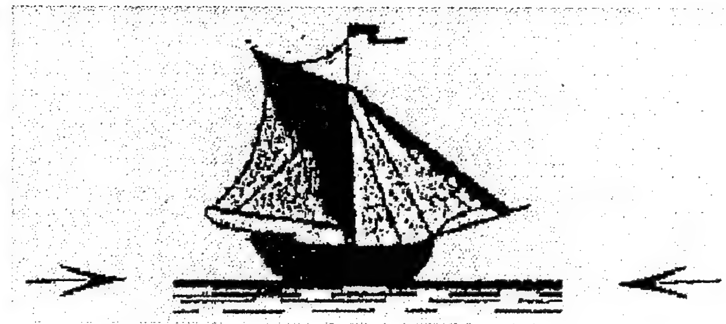

When the air becomes colder than the water, the atmosphere becomes unstable. The air next to the sea surface is warmed by the water and convection increases. This mixing of the air vertically, along with the wind moving the air horizontally, creates a horizontally uniform lapse rate. Atmospheric models are most accurate under these conditions.

Under unstable conditions, the range to the horizon is shorter than for neutral conditions. The horizon is also at a lower elevation. A mirage, known as the inferior mirage, often forms under these conditions. It is the inferior mirage that is seen on distant road surfaces on sunny days. It is called inferior because the mirage image forms below the original image.

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- Jargon:
  - Air-Sea Temperature Difference (ASTD) — Negative
  - Atmospheric Condition — Unstable
  - Refractive Condition — Sub-refractive

- Effects:
  - Convection — Much
  - Dip Angle — Increased
  - Horizon Range — Decreased
  - Scintillation — Increased
  - Model Predictions — Good
  - Mirage Type, Frequency — Inferior, Common

The ray trace is generated from that same set of meteorological data as before, except the air temperature is now two degrees cooler. The region on the right where the lower rays cross those above is called the mirage zone. An object in this zone is seen at two different elevation angles by the observer. The range to the horizon is now about 6.5 nmi. Again, only increasing the observer's height can increase the acquisition range to a low flying target.

In the picture, the boat is still held at 8.5 nmi. The lower hull is now obscured by the inferior mirage, which appears as an inverted image. The horizon is at a lower elevation than before.

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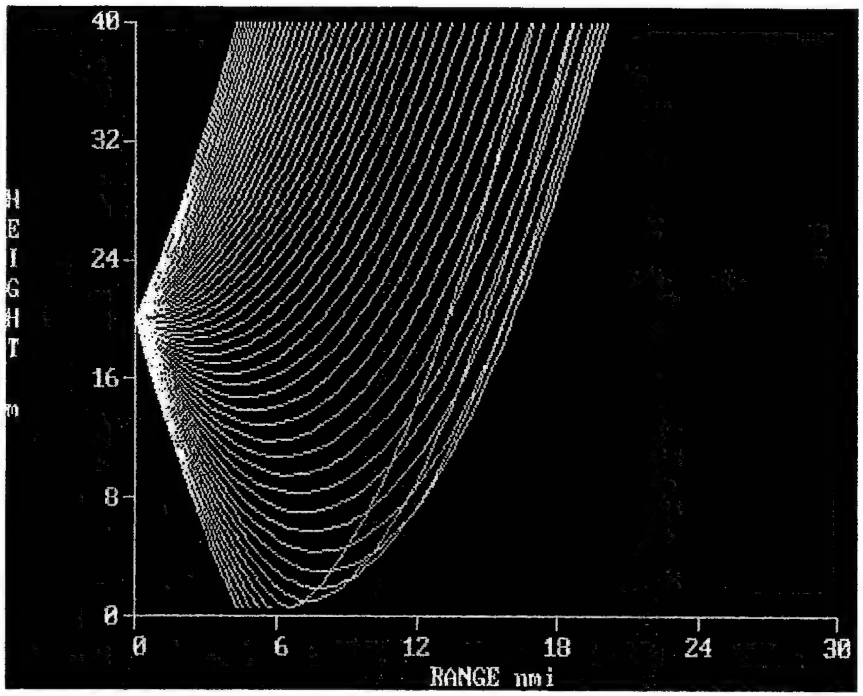
- Ray Trace:



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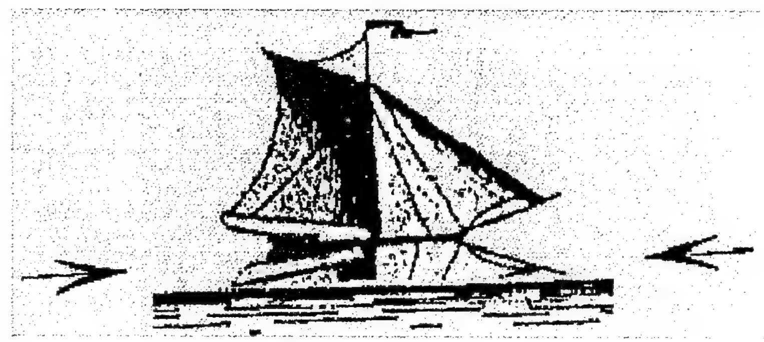

Stable conditions occur when the air temperature is warmer than the water temperature. This kind of profile discourages convection, reducing the mixing of the atmosphere. The atmosphere can even become stratified. Refraction models perform poorly under these conditions, since a stratified profile cannot be determined from only two temperature measurements.

Stable conditions produce an increased range to the horizon, and the elevation of the horizon is increased. A different type of mirage can be seen under these conditions, the superior mirage. The formation of a superior mirage depends upon the presence of a temperature inversion in the atmosphere, a layer of air warmer than that below. In a superior mirage, additional images appear above the original image. A single temperature inversion can create two additional images. However, the formation of this type of mirage can be quite complex.

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- Jargon:
  - Air-Sea Temperature Difference (ASTD) — Positive
  - Atmospheric Condition — Stable
  - Refractive Condition — Super-refractive

- Effects:
  - Convection — Little
  - Dip Angle — Decreased
  - Horizon Range — Increased
  - Scintillation — Increased
  - Model Predictions — Poor
  - Mirage Type, Frequency — Superior, Uncommon

The meteorological conditions used to generate this stable condition are identical to the previous cases, except the air temperature is now two degrees warmer than the water. The ray trace shows one of the problems with the refraction models. The temperature profile continues to increase with height. The rays of increasing elevation are bent back toward the Earth's surface, encountering it at increasing range. In the real atmosphere, there is height at which the air will begin to cool with increasing altitude. At that point, the rays will no longer bend towards the Earth, but away from it. Current atmospheric models do not predict the height at which this will occur.

The picture shows how objects in the field of view, such as the boat, are now at a higher apparent elevation. The horizon is both at a high elevation and now farther than the boat. Since the maximum range to a target is attenuation limited, the observer does not get a range increase by increasing the height.

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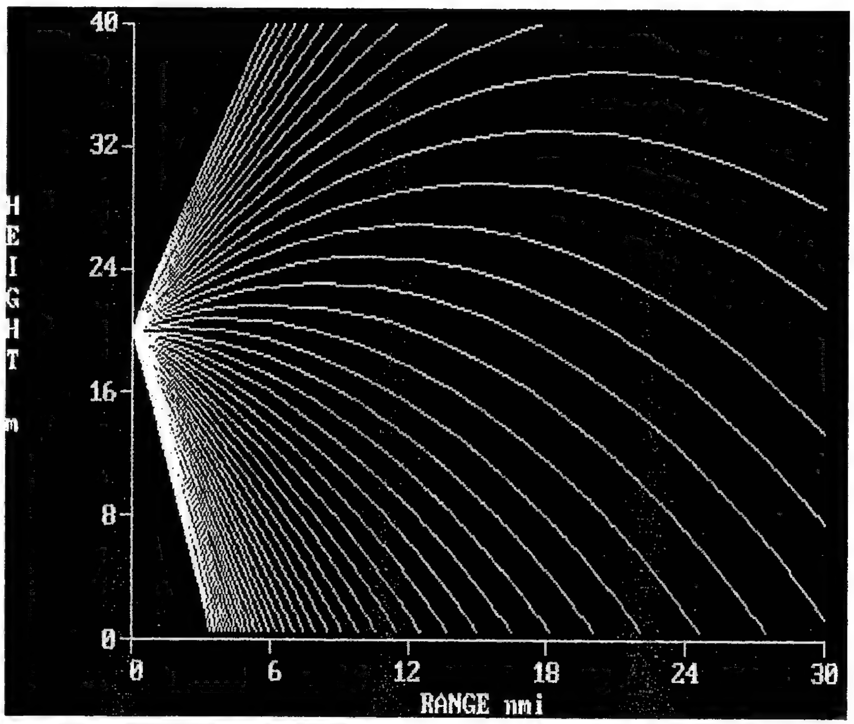
- Ray Trace:



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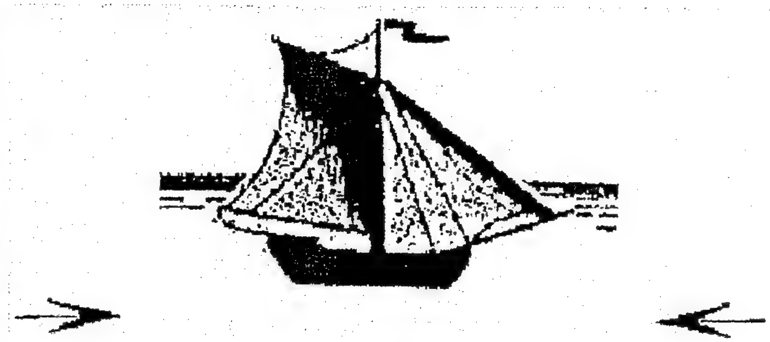

Conditions for this picture are the same as before, except that a temperature inversion has been added. At a level above the observer, the index of refraction was changed to show a higher than predicted air temperature. Rays passing into this stratum are bent down more strongly than those below.

As the elevation angle increases, the range to the source of the rays is increasing until about 22 nmi. At that point, the rays are being bent by the temperature inversion and the ranges to the sources actually decrease, for increasing observer elevation, to about 20 nmi. Thereafter, the ranges increase with increasing elevation. If the boat is placed at about 21 nmi, it would appear as shown. The rays sweep over that point three times producing the three images of the boat.

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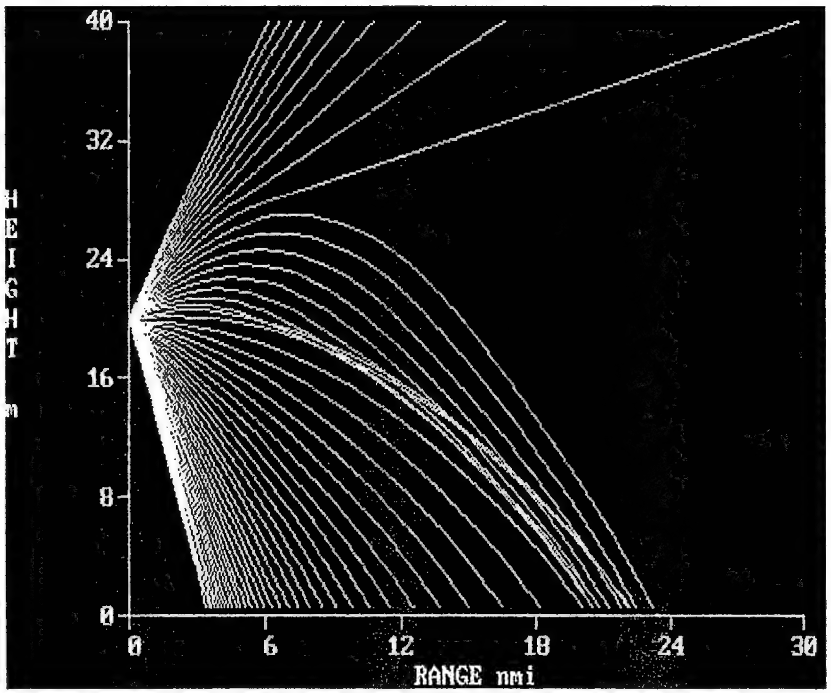
- Ray Trace:



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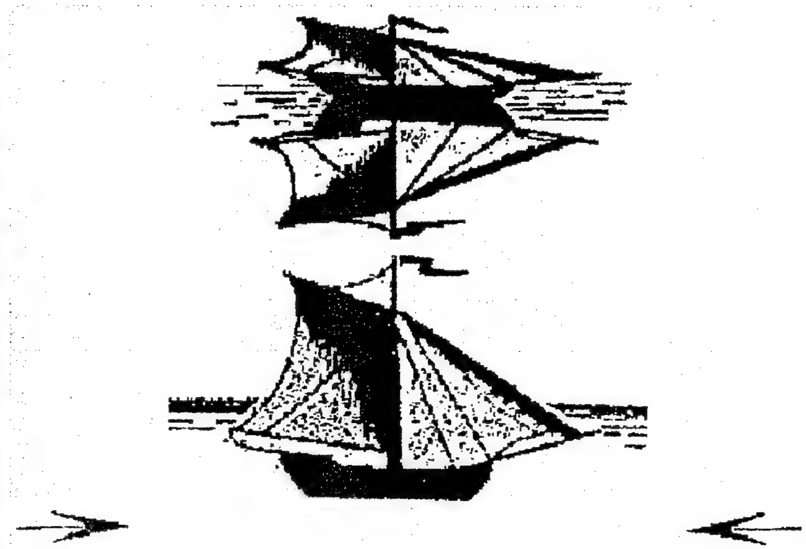


Parts of a recent field test, at Wallops Island, Virginia, were devoted to the measurement of infrared refraction effects.

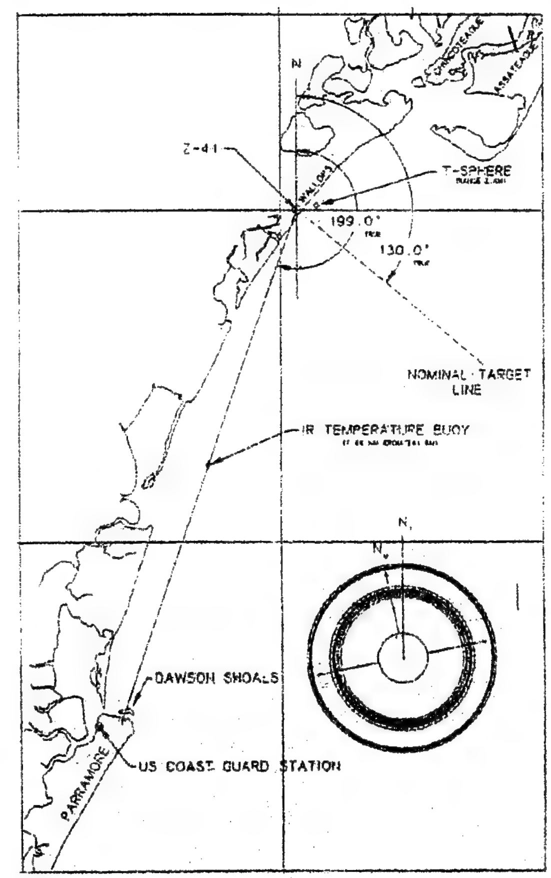
Heaters were mounted at fixed heights on the bow and stern of a boat. As the boat moved radially with respect to the sensor, the maximum possible range to the target could be measured.

A similar heater was mounted on a tower located at Parramore Island, about 16.2 nmi south-southwest from Wallops Island. The height of this heater could be set anywhere from 14.33 to 87.33 ft above mean sea level. Thus, for a fixed range, the refraction effects at various heights could be measured.

Other targets [an outbound Lear jet, and an inbound TLX-1] provided qualitative information of the atmosphere. The TLX-1 was a target towed by a Lear jet, which could be made to provide a infrared target.

- Targets
  - 20 W/Ster heater mounted on "Sealion"
  - 20 W/Ster heater mounted at Parramore Island
  - Lear jet
  - TLX

- Scenarios
  - "Sealion"
    Fixed heater height
    Radially inbound or outbound motion
  - Parramore Is.
    Fixed heater range
    Vertical motion on tower
  - Lear jet
    Low altitude, radially outbound flight
  - TLX
    Low altitude, radially inbound flight



There were two infrared sensors at the field test. The HISS is a research infrared search and track system. While not devoted to the propagation task, many of its measurements are applicable. The IRP sensor was actually part of a larger experiment to correlate propagation effects between the infrared and radio frequency bands.

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- HISS Sensor
  - 3.8 - 4.2 μm spectral band
  - 256 x 256 focal plane array
  - HgCdTe detectors
  - 80 x 80 μrad instantaneous field of view
  - 80 x 80 μrad spot size
  - 1.17v x 15h degree field of regard
  - Noise equivalent irradiance of 2e-14 W/cm2-ster
  - 1 sec scan update rate

- IRP Sensor
  - 3.9 - 5.1 μm spectral band
  - 256 x 256 focal plane array
  - InSb detectors
  - 33 x 33 μrad instantaneous field of view
  - 60 x 60 μrad spot size
  - 0.48 x 0.48 degree field of view
  - Noise equivalent irradiance of 3e-14 W/cm2-ster
  - staring

This photograph shows the setup of the HISS and IRP sensors on the roof of Building Z-41 at Wallops Island.

The HISS sensor is on the platform in the right of the picture. The height of its optical axis is 25.38 m above mean sea level.

The IRP sensor inside the wooden box is near the center of the picture. It is 22.03 m above mean sea level.

From this perspective, the Atlantic Ocean is behind the photographer.

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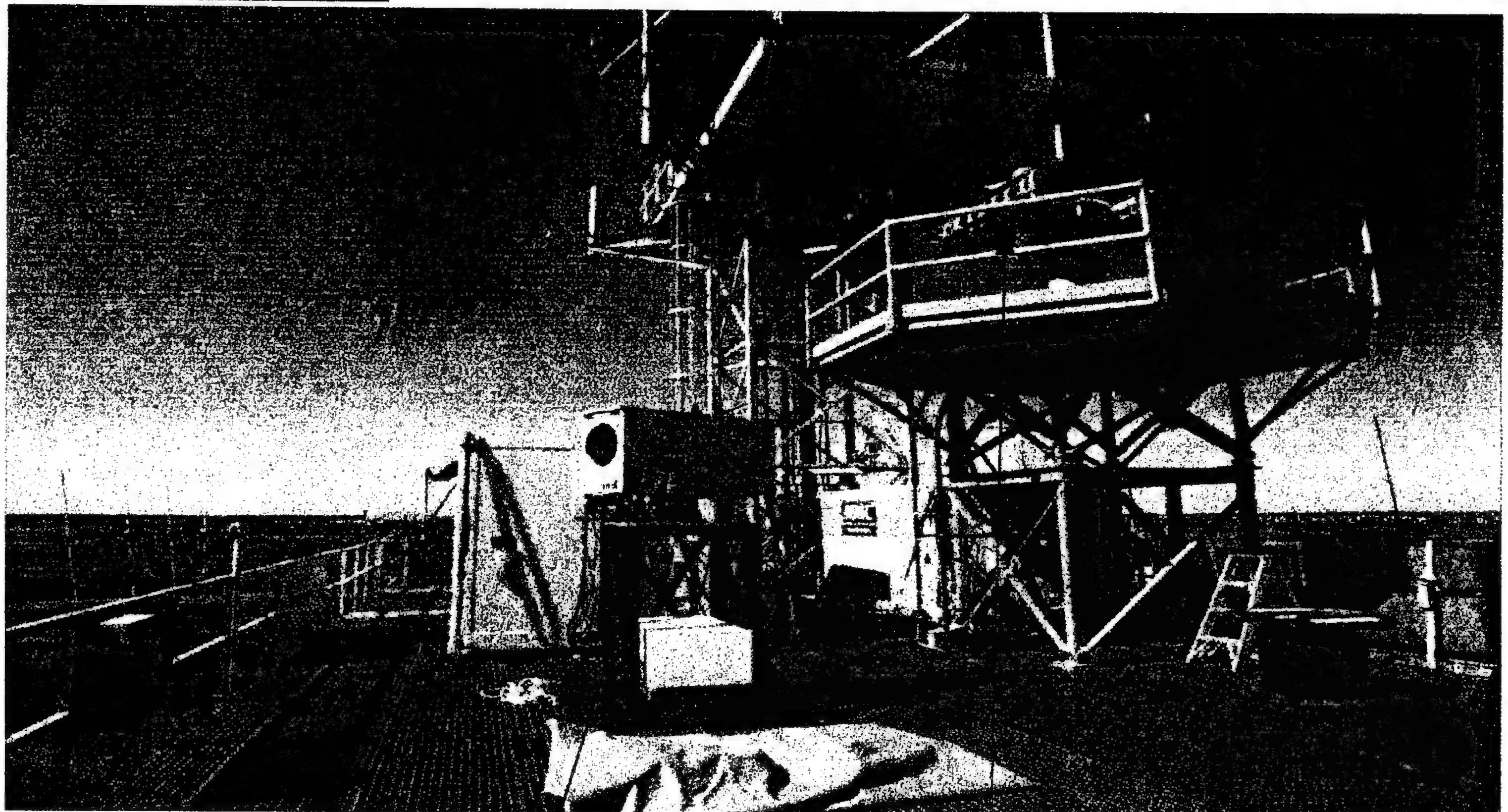
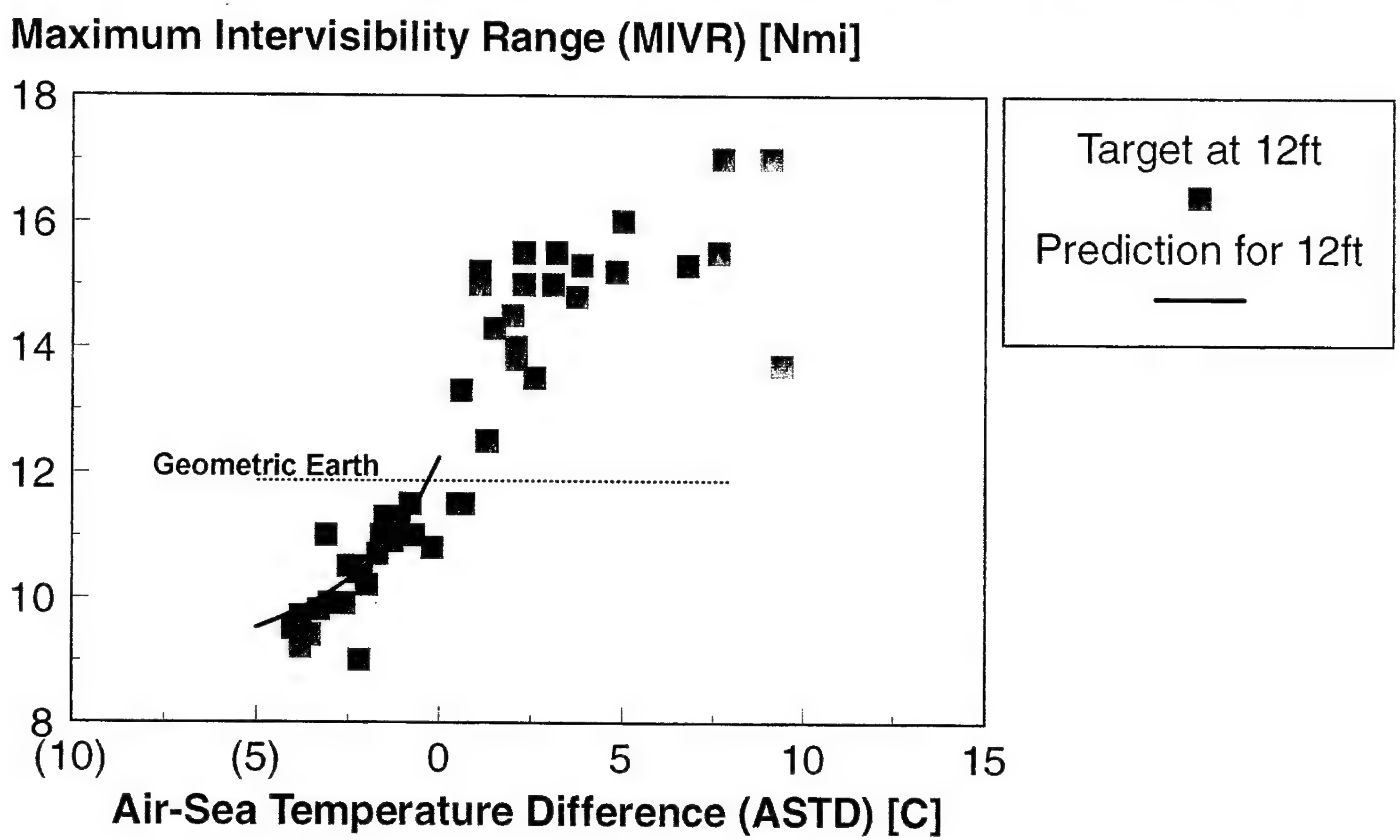


IRP sensor

HISS sensor

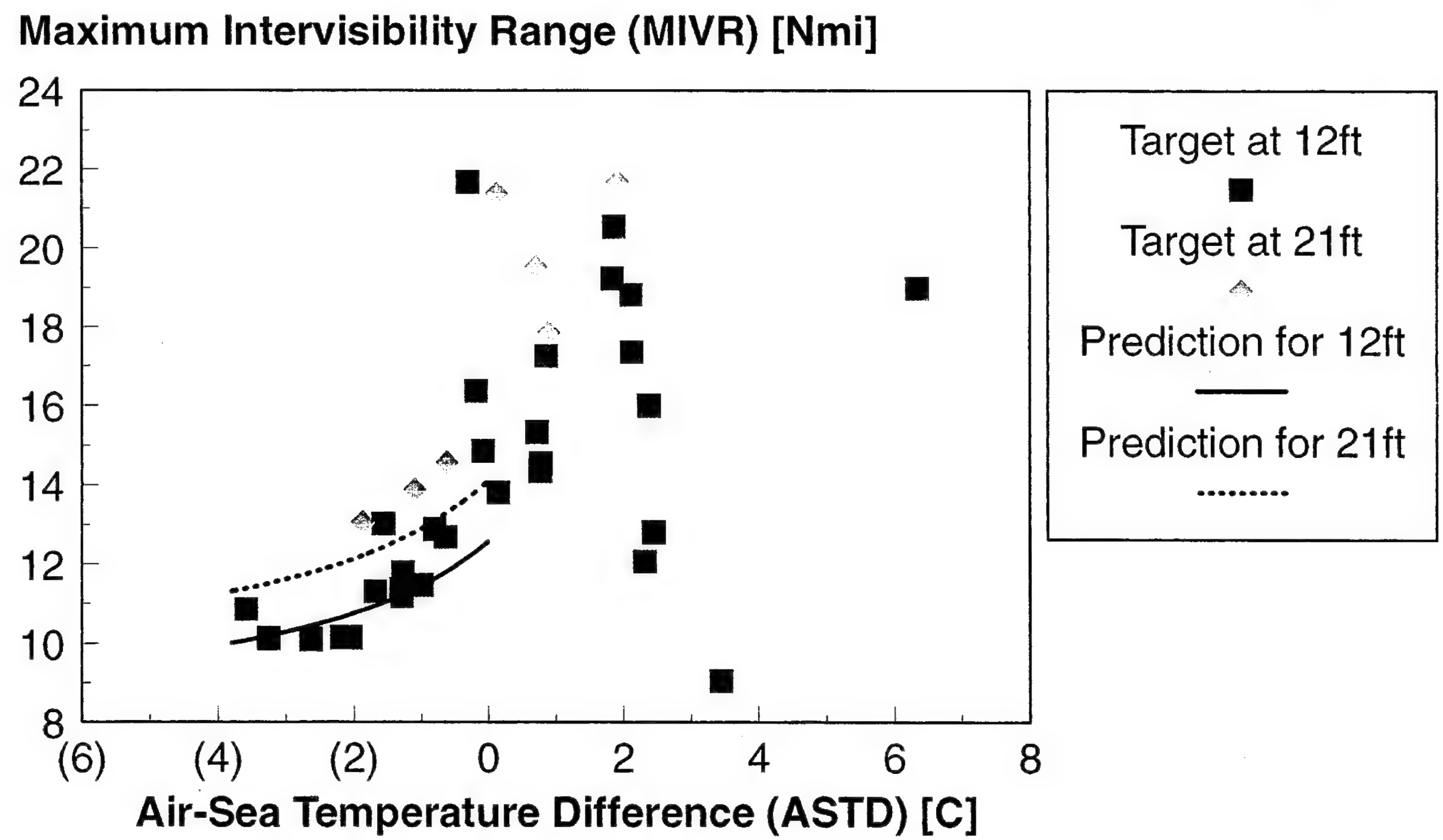
These are the maximum possible acquisition ranges that were measured in the HISS (PHASE I) field test. The predictions came from a formula developed by, the Defence Research Establishment (DREV), Valcartier, Quebec, Canada.

The data shows that refraction is a major factor in acquisition range.


Maximum Intervisibility Range (MIVR) [Nmi]
18
16
14
12
10
8
(10)
(5)
0
5
10
15
Air-Sea Temperature Difference (ASTD) [C]
Geometric Earth
Target at 12ft
Prediction for 12ft

This graph shows the maximum possible acquisition ranges to the heaters carried by *Sealion*, during the latest field test. The predictions are again from the DREV formula.

The poor performance on the day with the +3.4 °C ASTD was due to poor atmospheric transmission conditions, and not a refraction effect. Both field tests indicate that the behavior is well behaved for negative ASTD, and more variable for positive ASTD.


Maximum Intervisibility Range (MIVR) [Nmi]
24
22
20
18
16
14
12
10
8
(6)
(4)
(2)
0
2
4
6
8
Air-Sea Temperature Difference (ASTD) [C]
Target at 12ft
Target at 21ft
Prediction for 12ft
Prediction for 21ft

This viewgraph shows an example of an observed inferior mirage. March 11 was a day of unstable atmospheric conditions. The air temperature was at 1.7 °C, the water temperature 4.7 °C, for an ASTD of -3.0 °C. As the *Sealion* moved radially outbound, an inferior mirage of the target formed at the horizon, at 8.5 nmi. The two images eventually merged to one, which disappeared above the horizon at 10 nmi.

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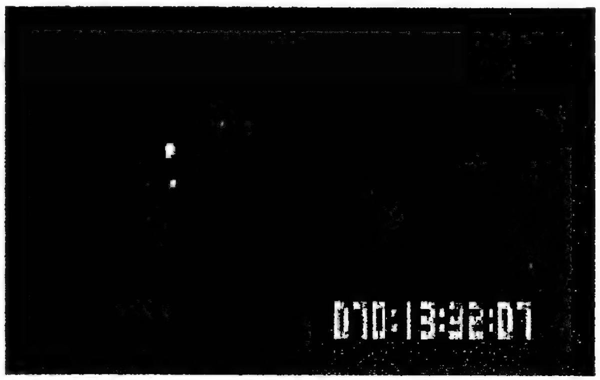
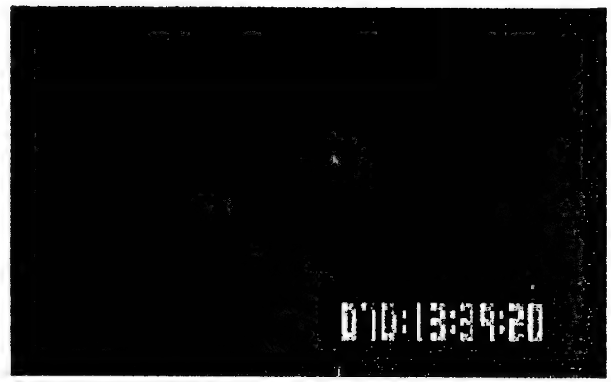


0.48 deg

"Sealion" at 8.4 nmi.



0.18 deg

0.48 deg

"Sealion" at 10 nmi.

These images show the inferior mirage of the heater on Parramore Island, also on 11 March. In this case, as the heater moves to a lower height, the two images merge and disappear when the heater moves below 66 ft.

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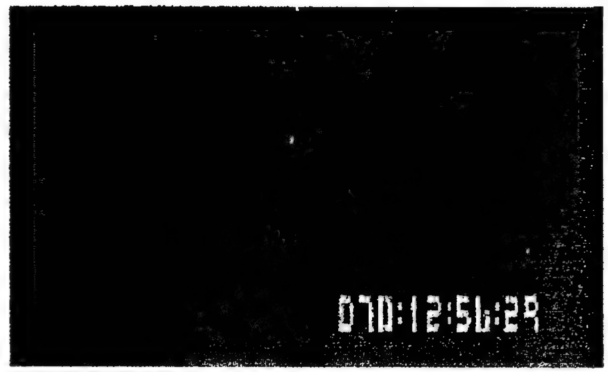
0.48 deg

Heater at 84ft



0.48 deg

0.18 deg

Heater at 66ft

March 1 was a day of unstable conditions. The air temperature was 2.6 °C and the water temperature was 3.7 °C for an ASTD of -1.1 °C. The observed test involved the *Sealion* making runs to the horizon when the Lear jet, which was involved in another test at the time, crossed into the field of view.

The sequence of pictures show the outbound Lear Jet entering the mirage zone. At that point, a second, inferior (lower) image of the Lear appears at the horizon. As the plane continues outbound, the two images coverage into a single image, which disappears above the horizon. Given the speed of the plane, the process took only a couple of seconds.

The *Sealion*, in the first picture is already closer than the range to the mirage zone.

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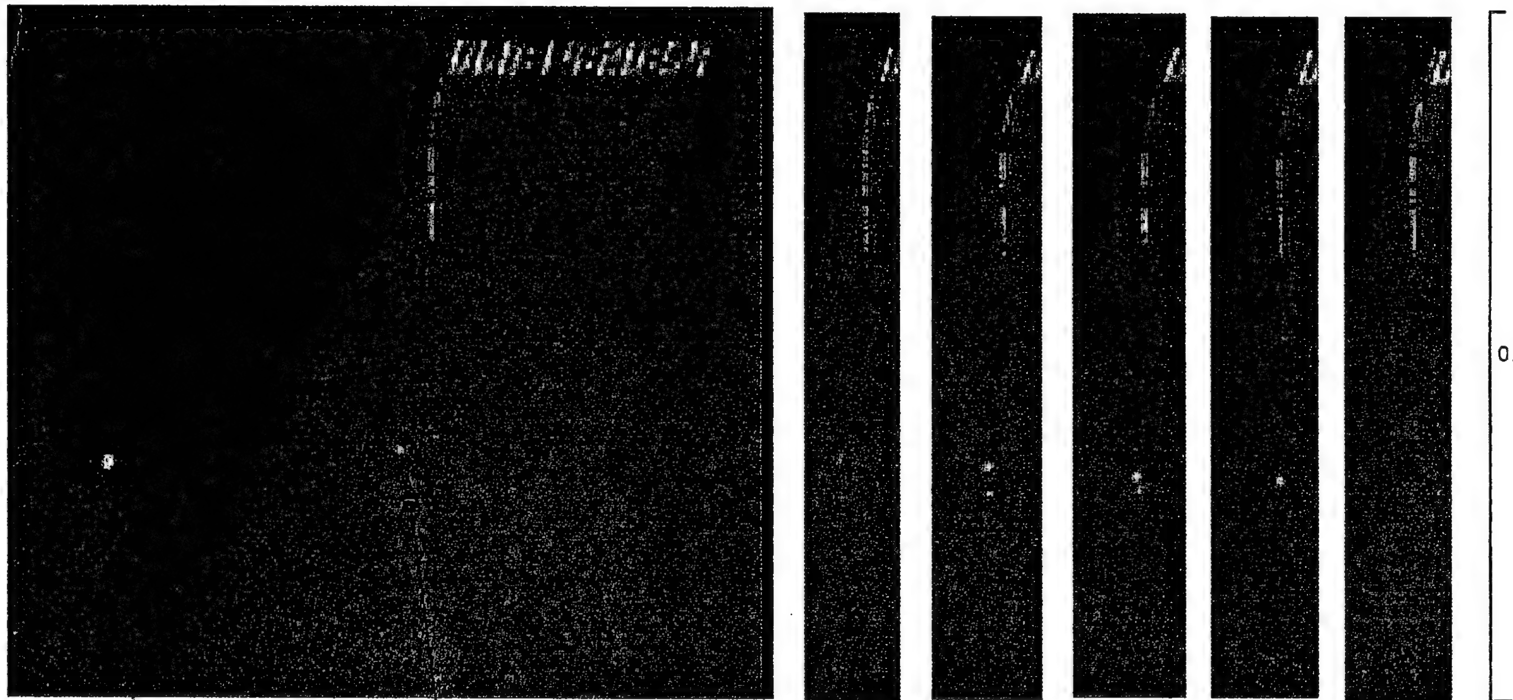

060:19:21:00 060:19:21:01

"Sealion" @ 10nmi Lear jet @ 30nmi, 560ft

0.48 deg

This viewgraph shows a rapid change in the elevation of the horizon in progress, seen on 23 March. The contrast of the pictures has been greatly enhanced to compensate for the loss in the printing process. The four images present a panorama of the sea. The horizon on the right is at a higher elevation than the horizon on the left. *Streamers* are rising up from the original horizon, moving from right to left, and filling in the space to the new horizon. In a matter of minutes, the effect moved across the field of view presented until no trace of the original horizon remained.

The effect points out a weakness of current refraction modeling. A set of temperature measurements at a single location cannot be adequate to cope with an effect that can be so spatially and temporally dependent.

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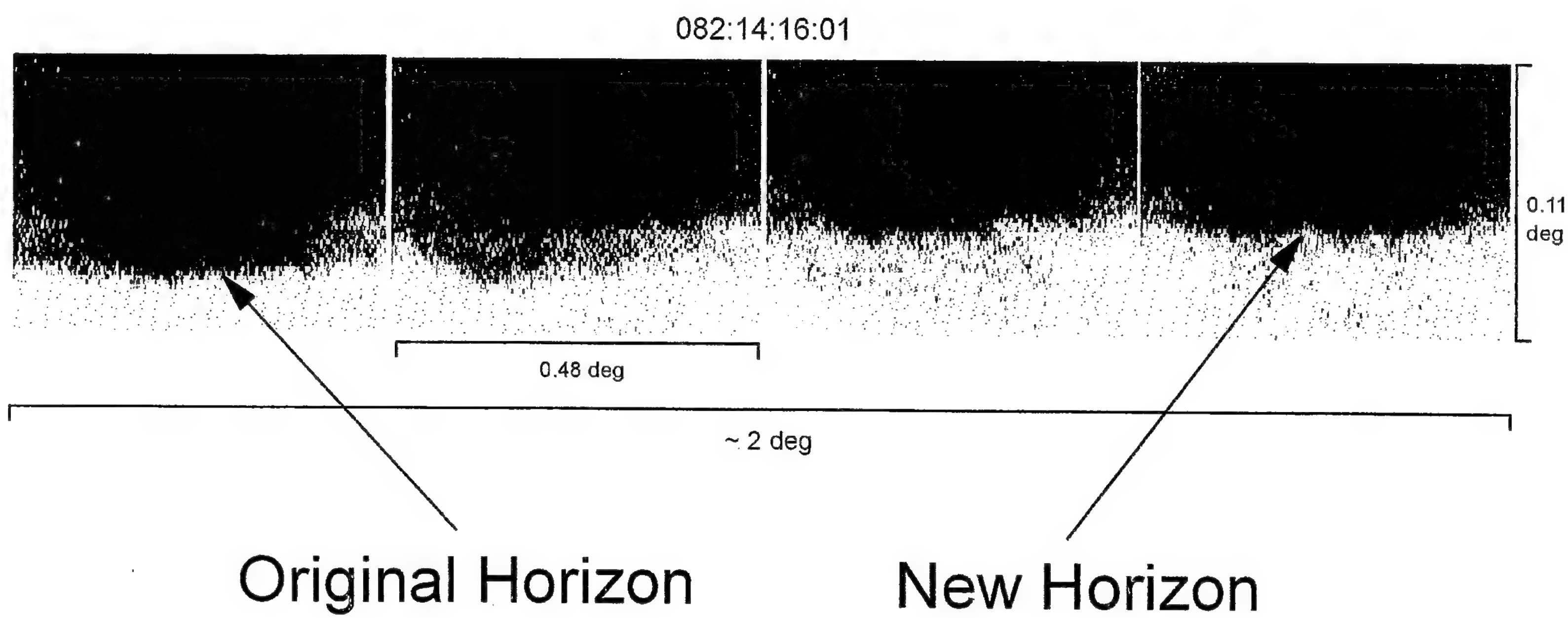
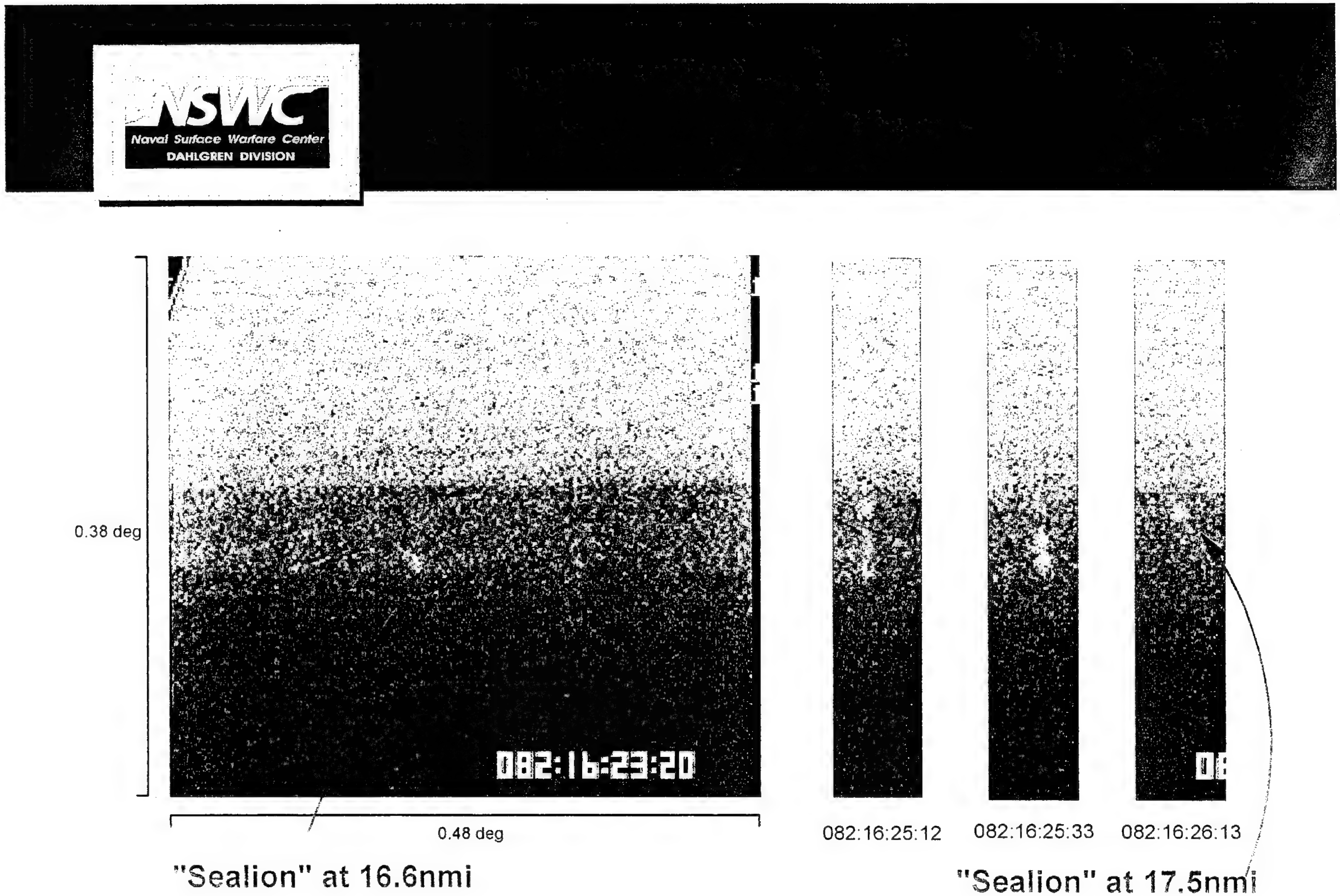


On 23 March, a superior mirage was observed. In the first picture, the *Sealion*, at 16.6 nmi, is already beyond the typical range to the horizon. Soon thereafter, two to three images of the target appear. As the range increased, the target became a single image again, at a noticeable higher elevation than before.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0.38 deg
082:16:23:20
0.48 deg
082:16:25:12
082:16:25:33
082:16:26:13
"Sealion" at 16.6nmi
"Sealion" at 17.5nmi

This viewgraph shows the dramatic increase in the elevation angle to the horizon that is possible under stable atmospheric conditions. Under most conditions, the *Sealion* at 12 nmi would be near the horizon. On this day, 24 March, a superior mirage has created a wall of water extending nearly 4 mrad above the "Sealion". Soon thereafter, the image of the *Sealion* faded from view, before it *climbed the wall* as in the previous day,

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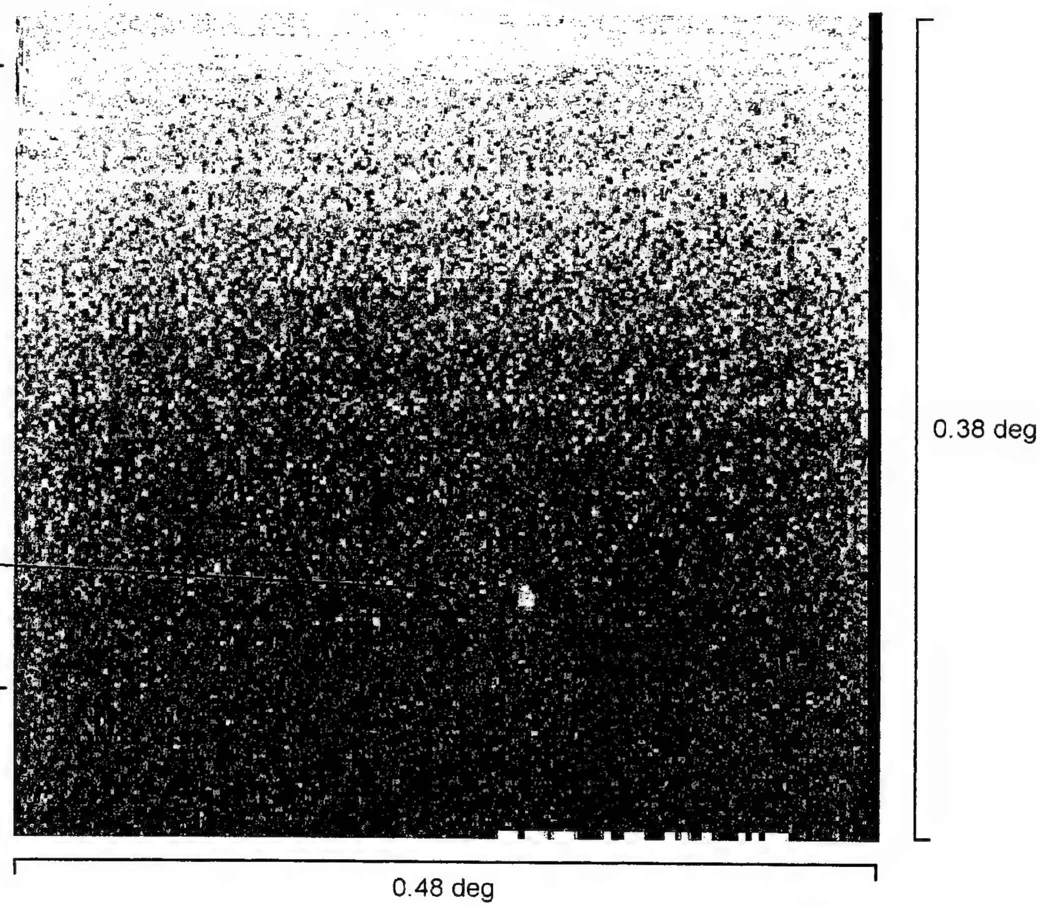

On 18 February, the *Sealion* made two outbound and two inbound runs to the horizon. During the first outbound run there was no mirage, only an increased range to the horizon. In the first inbound run, a small superior mirage formed for a short time. By the time of the second inbound run, shown in the picture, the superior mirage had become spectacular with multiple images of the target appearing and disappearing. The dark band, an image of the sea, would sometimes grow, sometimes disappear, with the horizon elevation changing as well.

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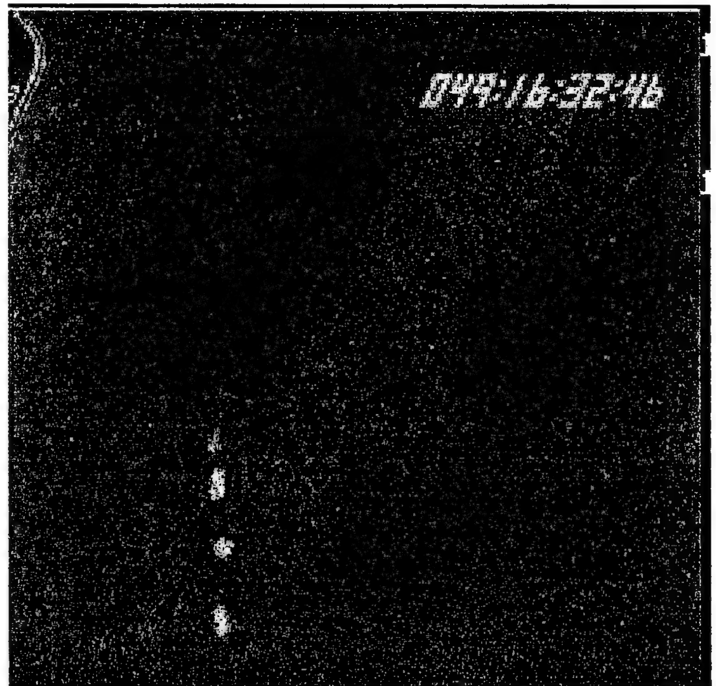

0.38 deg

0.48 deg

"Sealion" at 17.7 Nmi

This is another view of the superior mirages witnessed on 24 March. In this case, it is multiple images of the heater at Parramore Island.

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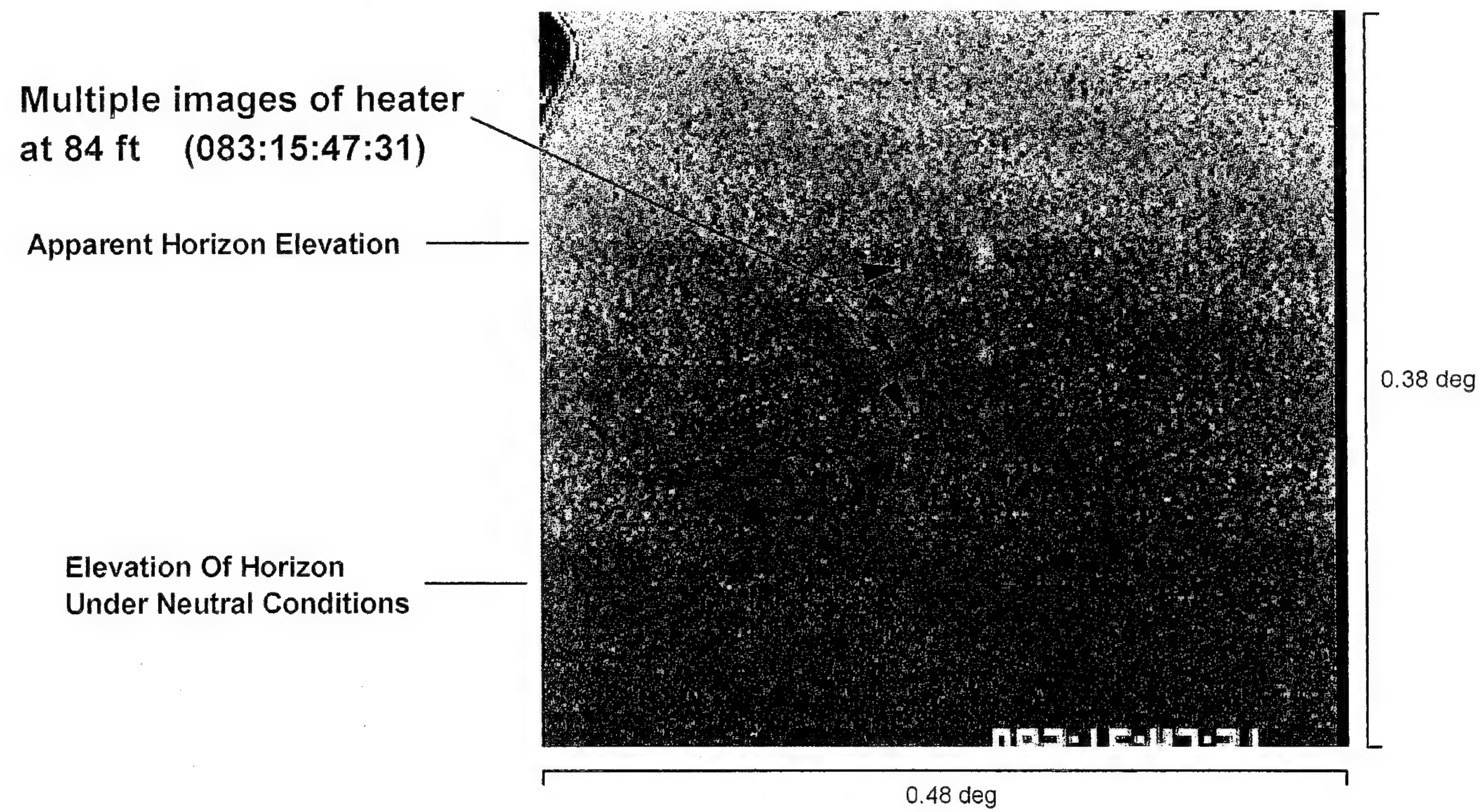

This is a superior mirage to the TLX target, on 24 March. When the target was first acquired, it appeared very blurred and distorted. As the range decreased, the image started to stretch vertically. A second image of the target emerged from the top of the field of view and merged with the first into a single image that faded from view. However, a fade zone cannot be inferred since the HISS began detecting the target at this point; another image of the target was above our field of view.

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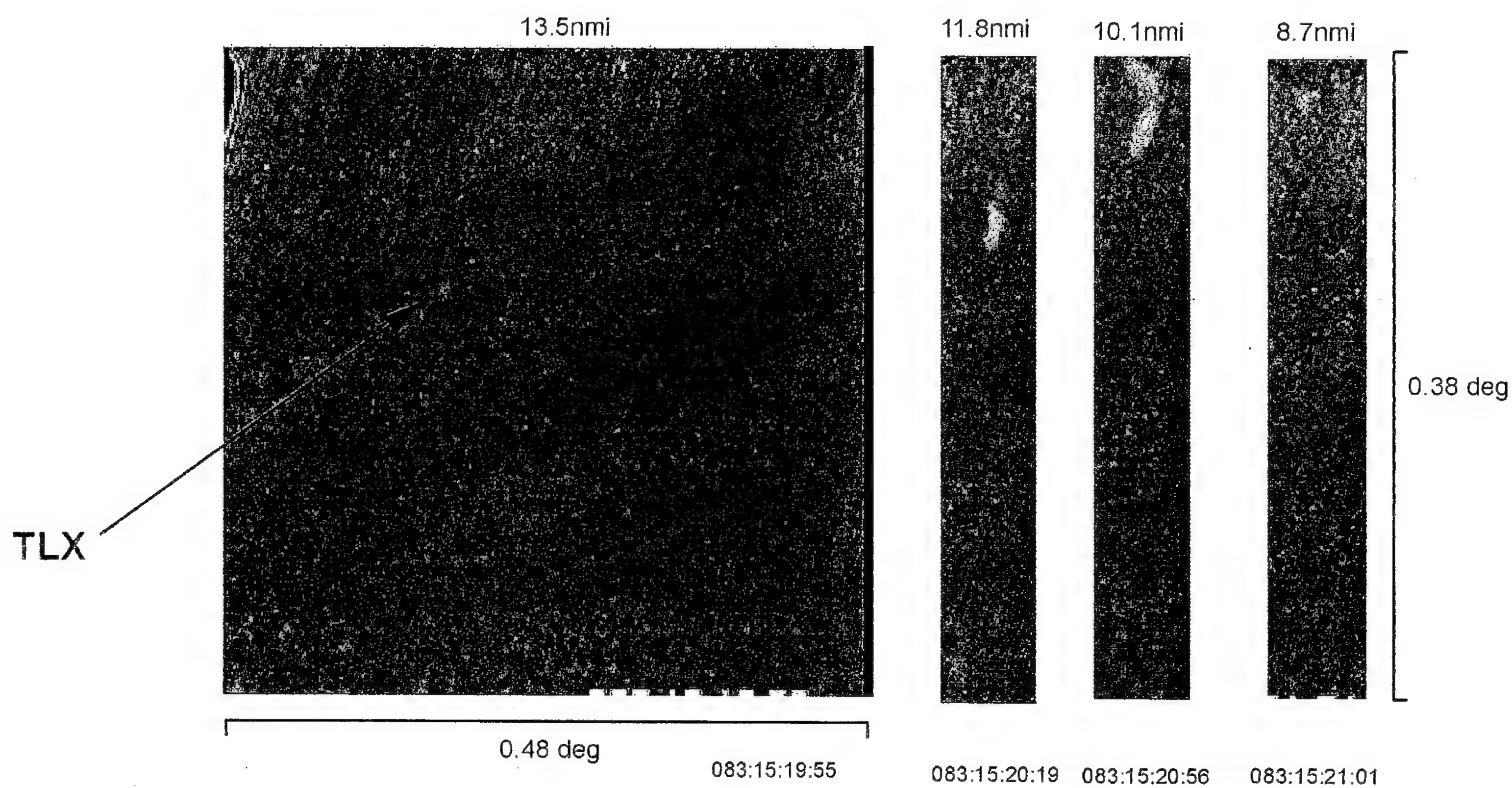

This viewgraph shows detections on an outbound Lear jet by the HISS sensor on 24 March. The detections and pictures of the target depict the formation of multiple images by a mirage. The gap in detections between 100 and 125 sec seems to be caused by a fade zone in which no energy was received from the target. However, in the gap occurring after 160 sec, the lowest image of the target remained in the video, though was too faint to exceed the HISS detection threshold.

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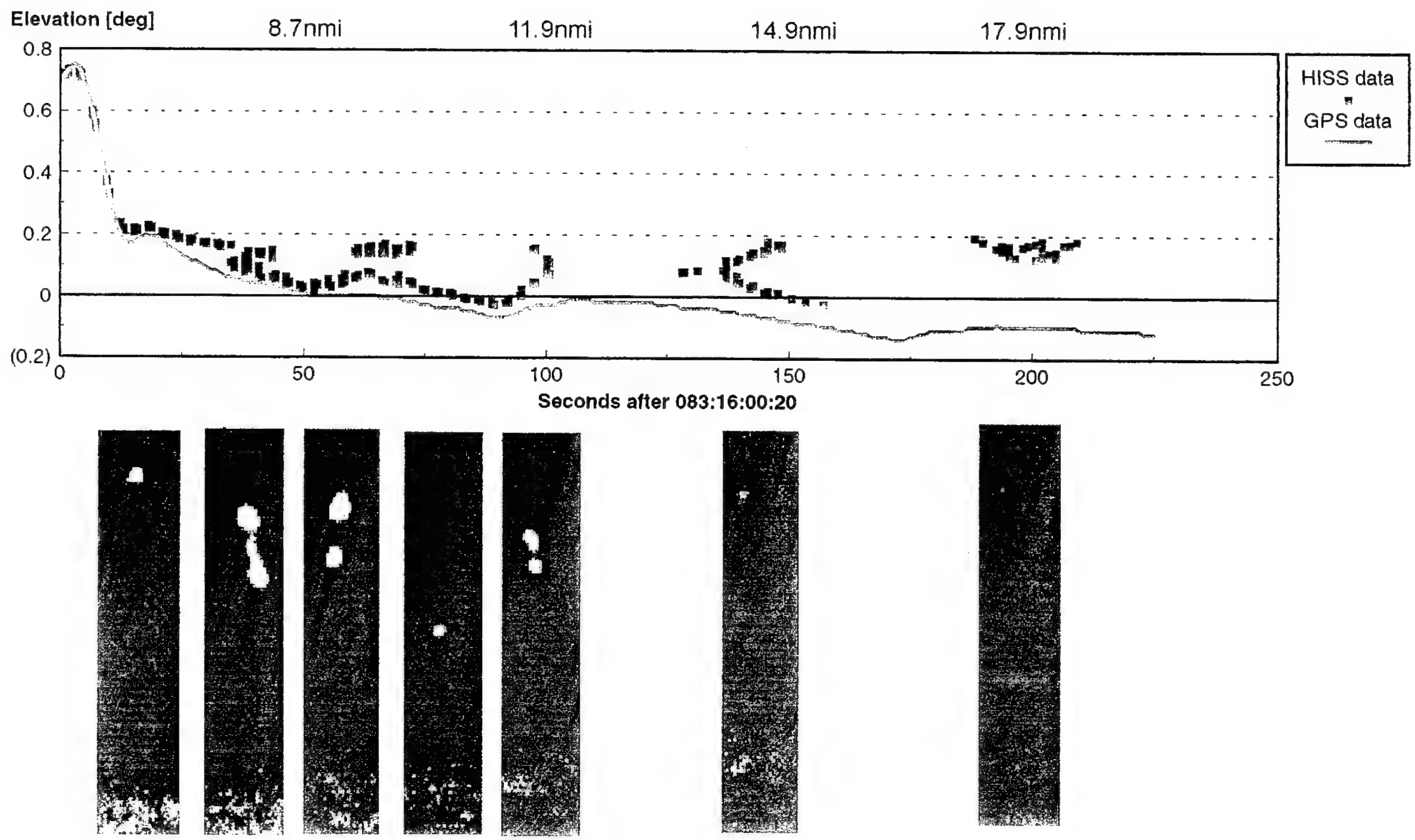
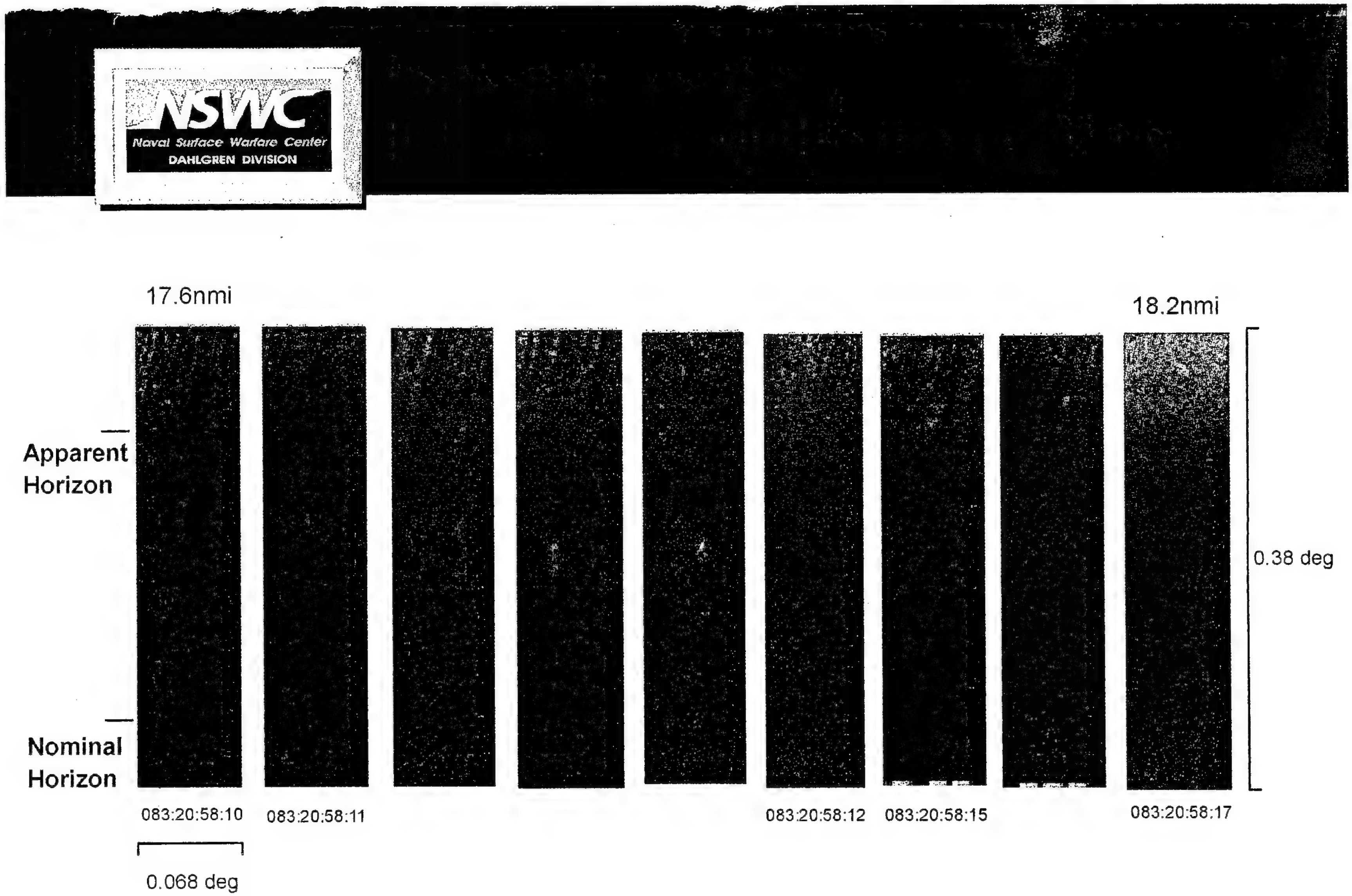


The outbound Lear jet was a difficult target for the IRP sensor to acquire and track, due to the very small field of view and awkward azimuth control. However, on 24 March, the effort produced a spectacular image of a superior mirage. (This is a different run than the HISS detections shown in the previous viewgraph.) The plane was acquired as two images that were below the horizon. The two images merged into one and disappeared for nearly 3 sec. The jet than reappeared as a single image at the horizon and, thereafter, increased in elevation.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17.6nmi
18.2nmi
Apparent Horizon
Nominal Horizon
0.38 deg
083:20:58:10
083:20:58:11
083:20:58:12
083:20:58:15
083:20:58:17
0.068 deg

Refraction observations were made on 29 days during the test period. On 14 days, we observed stable conditions; on 11 days, unstable conditions. Since neutral conditions are really a transition state, the four days that remained near neutral during our observations were arbitrarily listed as neutral.

Superior mirages were observed on six of the days with stable conditions. All 11 days of unstable conditions exhibited inferior mirages.

On two days, the superior mirages were spectacular and produced "fade zones". These were regions in which the target was not visible, but would reappear at longer ranges. On 18 February, the "Sealion" passed through two small fade zones on one outbound run. Then, on 24 March, Fade zones were observed in the outbound flights of the Lear jet. However, there were no fade zones observed during the "Sealion" runs on this day.

Met. Condition	Mirages	Fade Zones
Stable (Positive ASTD) 14 days	Superior 6 days	2 days
Neutral 4 days		
Unstable (Negative ASTD) 11 days	Inferior 11 days	

This field test proved many opportunities to observe different atmospheric conditions. This presentation illustrated the most spectacular mirages witnessed on five of the days. Several conclusions can be drawn from these observations.

Refraction effects are common and as changeable as the weather. In unstable atmospheric conditions, refraction is easily predicted from the air and sea temperature measurements. To accurately predict refraction effects in stable atmospheric conditions may require detailed temperature profiles at several points along the optical path.

The same conditions that produce mirages in the visible will produce infrared mirages. Inferior mirages are well behaved, but superior mirages are more difficult to predict. Superior mirages are sometimes associated with *fade zones* in which the target signature is greatly diminished. However, mirages are a long-range effect, and are usually short lived upon a radially moving target.

Naval Surface Warfare Center
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- IR refraction effects are common and are an important factor in the long range acquisition and tracking of a low altitude target.
- As weather conditions change, so to do refraction effects.
- The ability to predict refraction effects requires sufficient met collection.
- Atmospheric conditions that cause mirages in the visible band do so in the infrared as well.
  - Inferior mirages are common, with predictable effects.
  - Superior mirages are less common , with effects that are more difficult to predict.
  - IR "fade zones" are sometimes associated with superior mirages.
  - Mirages are dependent upon the target's range and height. It is a long range and, for a radially moving target, transient phenomenon.

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Mirages and other atmospheric refraction effects were observed and measured in the mid-wave infrared band (3 to 5 μm) during a recent field test. High-resolution recorded imagery is presented, including inferior and superior mirages. The affect of a superior mirage on target reporting by an infrared search and track simulation system is shown. This work is part of a continuing program to correlate IR refraction effects with simultaneous radio frequency propagation effects.

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